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Ranking the geothermal potential of radiothermal granites in Scotland: are any others as hot as the Cairngorms?

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Abstract: Prior investigations concur that the granite plutons in Scotland which are most likely to prove favourable for geothermal exploration are the Ballater, Bennachie, Cairngorm, and Mount Battock plutons, all of which have heat production values greater than 5 µW/m^3. This heat production arises from the significant concentrations of potassium, uranium, and thorium in some granite plutons. A new field-based gamma-ray spectrometric survey targeted plutons which were poorly surveyed in the past or near areas of high heat demand. This survey identifies several other plutons (Ben Rhinnes, Cheviot, Hill of Fare, Lochnagar, and Monadhliath) with heat production rates between 3 and 5 µW/m^3 that could well have geothermal gradients sufficient for direct heat use rather than higher temperatures required for electricity generation.

The Criffel and Cheviot plutons are examples of Scottish granites which have concentric compositional zonation and some zones have significantly higher (up to 20%) heat production rates than others in the same plutons. However, the relatively small surface areas of individual high heat-production zones mean that it is unlikely to be worthwhile specifically targeting them.

Supplementary material: The full set of heat production data are available at: http://dx.doi.org/10.5525/gla.researchdata.302

Renewed geothermal exploration worldwide is being driven by the need to provide low carbon renewable energy (Younger 2014). The last drive in British geothermal exploration concentrated on identifying resources capable of generating electricity. At this time the Scottish granites were identified as lacking the required geothermal resources due to the very high temperatures (>130°C) and production rates required for power generation. Renewed interest in the geothermal potential of the Scottish granites has recently emerged for two reasons. Firstly, a change in proposed exploitation from electricity generation to direct use heat; requiring much lower temperatures. Secondly, rigorous re-assessment of heat flow leading to an upgraded geothermal resource potential; suggesting higher temperatures at shallower depths than previously thought.

In Scotland, heat is currently responsible for over 55% of energy demand and electricity only 20% (The Scottish Government 2016a). Hence the modern interest in geothermal for direct use heat purposes. This paper focuses on the case of Scotland due to its acute need for renewable heat as the country only generates 3% of heat from renewable sources; compared to the EU average of 16% (Scottish Government 2016a). The Scottish Government has set a target of producing 11% of heat from renewable sources by 2020, so to meet this target there needs to be a sudden and sustained growth in renewable heat capacity. Currently, 90% of Scotland's renewable heat output is from biomass (Scottish Government 2016a), however widespread uptake of biomass for district heating schemes is hampered due to particulate and NO$_x$ emission standards in cities. Geothermal resources remain a hitherto untapped supply of large scale renewable heat with no emission or additional infrastructure issues which could block development in cities or other locations of high heat demand (e.g. distilleries and other heat-intensive industries).

Granite geothermal reservoirs are one of the three principal geothermal resources identified in Scotland, the others being hot sedimentary aquifers and abandoned mine workings (Gillespie et al. 2013). Granite geothermal resources arise where plutons are naturally enriched in potassium, uranium and thorium. The natural radioactive decay of these elements produces heat. Despite this heat production being relatively small (on the order of several $\mu W/m^3$ of granite), the large volumes of the granite plutons (e.g. Rollin 1984) means there is often sufficient heat-producing rock available to materially elevate the geothermal gradient beyond that of the background heat conduction from the mantle. The geothermal potential of the granites of Scotland was previously investigated as part of the UK-wide assessment of the potential for new sources of electricity generation in the 1970s and 80s (Downing and Gray 1986). Gamma-ray spectrometric surveys identified four high heat producing granites in Scotland; Ballater, Bennachie, Cairngorm, and Mount Battock (Fig. 1). The findings of these gamma-ray surveys were summarised by Downing and Gray 1986 (their Table 3.9). However the original data and methods are documented in a range of sources, including in-house BGS reports (Webb and Brown 1984), theses (Barritt 1983, Tindle 1982, Cassidy 1979, and Hennessey 1979) as well as various reported personal communications. Different methods were also reportedly used, including Instrumental Neutron Activation Analysis (INAA), X-ray fluoresence (XRF) or vague “field based techniques”. Furthermore, some granites plutons only yielded small numbers of heat production values, resulting in estimates which are not robust. Shallow (≤ 300m) heat flow assessment boreholes were subsequently drilled into the four granite plutons identified as high heat producing. The heat flow results from these boreholes were much lower than expected (Wheildon et al. 1984) and predicted low geothermal gradients. Consequently, exploration of the Scottish granites was discontinued. However, these studies neglected to correct the heat flow measurements for the cooling effects from periods of lower temperatures during the Pleistocene. That past climate can affect temperature in boreholes of several hundred metres depth was established decades ago (e.g. Anderson 1940). This effect is expected to be particularly acute in Britain, due to the large temperature differential between modern times and past ice ages largely a result of the current warming effect of the gulf stream. Recent palaeoclimate corrections suggest that these granites represent significantly better resources than was previously realised (Westaway and Younger 2013, Busby et al. 2015). Topographical influences were also corrected for by Westaway and Younger (2013) and Wheildon et al. (1984) which had the effect of reducing the heat flow estimate by approximately 5%.

The corrected heat flow measurements combined with the current exploration being for direct use heat, mean that geothermal exploration and production would be at much shallower depths than previously considered. This has the effect of significantly reducing drilling costs and risk, lowering the significant economic barriers to the first steps of geothermal development. Although the previous gamma-ray spectrometry survey identified four high heat producing granites, other plutons were poorly surveyed e.g. the Hill of Fare pluton had only two measurements. To re-evaluate the radiogenic heat production properties of Scottish granite a new gamma-ray spectrometry survey has been conducted. The survey aims to reduce uncertainty over granite geothermal resources in Scotland by providing new heat production data for previously poorly surveyed granites. These data are made freely available so any assessment using these data can better understand how the heat production estimates were reached. The new data may also indicate possible granite geothermal resources that have previously been overlooked.

Geological Setting

The majority of Scottish granite plutons (and those of interest in this study) were emplaced following the Caledonian Orogeny and after final closure of the Iapetus during the late Silurian and Early

Devonian (Thirlwall 1982, Stephens and Halliday 1984, Miles et al. 2016). Biostratigraphic (Kemp 1987) and geochronological (Rock et al. 1986 and Kneller 1991) evidence provides a time of 420 Ma for final closure of the Iapetus. The post-Caledonian granites were emplaced between 435 and 390 Ma (Halliday and Stephens 1984) but the majority were emplaced between 410 and 400 Ma (Soper 1986). Magma was likely generated due to slab breakoff during collision of Baltica with the Scoto-Greenland margin (Atherton and Ghani 2002). The post-collisional regime of transpression and transtension resulted in the large lateral movements along the Great Glen and Highland Boundary Faults.

The Scottish granites inherited their isotopic signature from their host terrain (Stephens and Halliday 1984, Thirlwall 1989 and Canning et al. 1996) and the post Caledonian granites were emplaced over a similar time period (Miles et al. 2014). The granites are classified into four terranes: the Argyll and Northern Highlands Suite, the Cairngorm Suite, the South of Scotland Suite, and the Galloway Suite/Trans-Suture Suite (Highton 1999 and Miles et al. 2014). The Cairngorm Suite made up the granites which were previously identified as the best geothermal granite resource and these tend to have higher SiO2 contents and have generally evolved geochemical characteristics (Downing and Gray 1984). Original interpretations of the post-Caledonian granites suggested emplacement was in analogous settings to Andean type subduction arcs. However there are significant compositional differences between the Caledonian Granite and granite in such an Andean environment (Pitch 1983, Miles et al. 2014). Such disagreement testifies to the continuing research revealing ever increasing emplacement complexity of the Caledonian Granite than previously thought.

A much younger suite of Tertiary granites in Scotland is represented in this study by the Arran granite. In contrast to the Caledonian granites, the Tertiary granites formed in response to emplacement of the Iceland mantle plume

Methods

Plutons Targeted

In Scotland, there are many more distinct granite plutons than are covered in this study. Plutons were targetted in this study if they fulfilled one or more of these factors: whether the pluton had relatively few existing heat production data, whether the pluton was located near places of significant heat demand, and / or the pluton was previously considered a high heat producing granite.

The Arran and Strathspey granites had no previous heat production data (locations shown on Fig. 1). Many Scottish granites had fewer than ten heat production data points, these were; Aberdeen (with a mean heat production of 2.2 µW/m^3, and n=3), Ardclach (1.4 µW/m^3, n=4), Ben Rhinnes (3.2 µW/m^3, n=6), Cheviot (3.0 µW/m^3, n=6), Grantown (1.3 µW/m^3, n=6), Hill of Fare (3.9 µW/m^3, n=2), Monadhliath (5.7 µW/m^3, n=6), Moy (2.1 µW/m^3, n=6), and Ross of Mull (1.5 µW/m^3, n=4). Many other Scottish granites also had similarly few heat production data but the surveying focussed on those plutons nearer centres of heat demand and / or of larger exposed surface area. The Ballater (5.7 µW/m^3, n=34), Bennachie (5.7 µW/m^3, n=32), Cairngorm (5.0 µW/m^3, n=233) and Mount Battock (5.0 µW/m^3, n=48) granites were previously well surveyed but are included in this current survey to allow comparison between these likely high heat producers and the granites with lower heat production. Lochnagar (2.7 µW/m^3, n=14) and Criffel (2.2 µW/m^3, n=14) had fourteen and eighteen measurements respectively. Despite this current low heat production estimate Lochnagar is re-evaluated because of its close proximity and chemical similarity to the high heat-producing East Grampian granites (Webb and Brown 1984), which suggests it may have previously been underestimated. Whereas the proximity of the Criffel granite to the large heat demand of the town of Dumfries justifies a re-evaluation with a more robust estimate of heat production.

Gamma-ray spectrometry measurements in the field

A GAMMA SURVEYOR II (GSII), manufactured by GF Instruments in Brno, Czech Republic, was used to collect data from all the granites in this study. Using the same equipment and methods for each granite ensures the readings would be consistent and directly comparable. The GSII uses a detector made of Bismuth Germanate Oxide with a volume of 20cm^3. The analyser measures 1024 channels between 0.03 and 3 MeV. The detector material reacts with gamma-rays and produces photons of visible light. These release of these photons forces electrons to be ejected from another component, called the photomultiplier. These electrons then strike an anode producing a negative voltage pulse proportional to the energy of the incident gamma-ray photon. Analyzers within the GSII then use the combined pulses over minutes of readings to produce estimates for potassium, uranium, and thorium contents as radioactive decay from these elements produces gamma-rays of different energies. For further details of the workings of gamma-ray spectrometry and geothermal exploration we refer the reader to McCay et al (2014). The GSII was chosen for these surveys because it is not prone to significant signal drift caused by temperature and other influences, and thus does not require daily calibration. It is also a compact and relatively light device (weighing only a few kilograms) so is easy to carry in the mountainous and remote terrains which host most of the granite exposure in Scotland. The output of the GSII provides information on the concentrations of potassium (as percentage by weight), uranium and thorium (both as parts per million). These concentrations are readily converted into equivalent radiogenic heat-production rates, as explained below.

To take measurements the GSII was placed directly against an exposed area of granite. Gamma-rays can penetrate up to 0.5 m through rock, however the half-lengths of gamma-rays mean that the majority of the detected photons will come from the shallowest 15cm of rock with a smaller contribution from deeper sources. This effectively results in the sample collecting information from a 15ch thick disc or rock which is 1m in radius (McCay et al. 2014). Raising the GSII above the ground would allow a much larger sample size to be effectively measured (e.g. Løvborg et al. 1979), due to gamma-rays being able to penetrate several hundred metres through air. However this elevated reading would be affected by the soil and vegetation cover on the rock so we opted for direct measurements to get a less ambiguous representation of granite heat production rates. The GSII is calibrated to take readings from a flat area of rock. If the measurement is taken in a depression then the readings will be overestimated due to gamma-rays from the overlooking areas of rock hitting the spectrometer, whereas if the measurement is on a mound that the readings will be underestimated (McCay et al. 2014). Measurement time was between 3 to 5 minutes as this gave the best balance between accuracy and speed. For each sample, at least two measurements were taken, if these were not sufficiently similar (within 10% of the U value) then further readings were taken until consistent readings were gathered.

Data Processing

The concentrations of potassium, uranium, and thorium provided by the GSII were used in the following equation to estimate heat production (HP):

$$HP(\mu W m^{-3}) = \rho\,(0.035C_K + 0.097C_U + 0.026C_{Th}) \qquad (1)$$

Where: ρ is rock density (kg m^{-3}), C_K is concentration of potassium by % weight, C_u and C_{Th} are concentration of uranium and thorium in ppm. The potassium % weight used for heat production is elemental, as opposed to percentage weight of K_2O used in other fields such as hydrogeology. The constants before each elemental concentration in equation 1 are based on the energy released during alpha, beta, and gamma decay of the radioelements (Birch 1954 and Rybach 1976).

Given the practical difficulty in obtaining and transporting granite samples, and the protected status of some of the sites we surveyed, we did not take samples from each measurement location in order to find the density of granite. Instead we assumed a density of granite of 2.7g/cm^3 for all samples based on information from the (Rollin 2009). For an example of how this assumption may influence the results, a sample with heat production of 4µW/m^3 with a density of 2.6 would have a change of heat production of +/- 0.2 µW/m^3 with a variation in density of +/- 0.1 kg/m^3. Although this is not an insignificant influence on heat production it is not enough for a granite pluton to be incorrectly identified (or dismissed) as of high heat production.

The arithmetic mean of the measurements was used to create an estimate of heat production for each pluton. Geometric means might be more appropriate in such a geological distribution due to the arithmetic mean losing information about the small scale hetereogeneties in heat production observed in some locations, which could be due to the incremental emplacments of plutons over tens of millions of years (e.g. Glazner et al. 2004). For example, the Mount Battock pluton has an area approximately 2m^2 where heat production is 15µW/m^3. However arithmetic mean is preferred to be consistent with the previous literature on heat production data in the United Kingdom (e.g. Downing and Gray 1986). Any measurements which were noted in the field as being influenced by nearfield topography (Tyler 2000) were removed prior to averaging (for information these data are still included and clearly identified in the database linked to this paper). Many of the measurements from the Hill of Fare granite were overestimates because they were collected within abandoned quarries. A bespoke method was developed to deal with these issues in this plutons which is explained below. Finally the calculated arithmetic means were combined with those of previous studies presented in Downing and Gray (1986).

Correction for overestimation in Quarry Measurements

Many sample locations of the Hill of Fare pluton were taken from abandoned quarries. These quarries have the advantage of being relatively fresh faces as they have not exposed to erosion for as long as the natural outcrops. However 10 of these sample locations had the disadvantage that the nearby quarry walls and ledges would lead to overestimated results. There are no standard methods detailed in the gamma-ray spectrometry literature to deal with such problems, so a novel solution is proposed here. Potassium shows the most consistent concentrations of the three radio-elements in granites so it is the variation in uranium and thorium concentrations that generally determine higher and lower heat production zones. Weight percent K in granite is typically between 3.8 and 4.5 for the East Grampian Siluro-Devonian granites (Table 3.9 Downing and Gray 1986), which is the suite to which the Hill of Fare granite belongs. However values of potassium concentration in the quarries were consistently higher than 5.0 indicating that they are likely overestimates due to the other quarry walls and surfaces.

The GSII is calibrated to be accurate when placed on a flat surface, the spectrometer effectively samples radiation incident from a solid angle of 2π steradians or a half space (Fig. 2). Hypothetically, a spectrometer placed underground would sample from and angle of 4π steradians or a full space, as it would be completely surrounded by radiogenic rock (Fix x – quarry effective sample volume). The shape of the quarries meant that the sample was effectively from 3π steradians or a three quarters space. This 3π sample volume should lead to an overestimation of the concentrations of radioelements by approximately 50%.

Such an overestimation would affect all three radio-element estimations by the same proportion. So if a “true” value of one of the radio-elements was known, then the ratio between that true value and the spectrometer estimation would indicate the degree of overestimation.The concentrations of potassium have previously been relatively consistent in high heat production granites compared with uranium and thorium. Downing and Gray (1984) report that high heat producing granites in Scotland have average potassium concentrations ranging between 4.1% and 4.4%. On the Hill of Fare granite, flat surface measurements were consistent with this trend giving values ranging between 4.0% and 4.8%. When tested against quarry faces (i.e. the quarry effective sample volume on Fig. 2) the GSII gave a potassium concentration of 7.14%. Which is 60-70% higher than what would be expected from a flat surface, but in-line with the enhancement expected from a 3π steradian, or greater, sample volume.

From the above test a method was developed to normalise potassium, uranium, and thorium values. A "true" value of 4.5 was assumed for potassium concentrations. Then, all three of the radioelements were divided by the ratio between the measured potassium and the assumed "correct" value of 4.5. For example, if a potassium concentration value in the quarries was measured as 9.0, then the correction factor is 4.5/9.0 which is 0.5.The potassium, uranium, and thorium concentrations would need to be halved to achieve a corrected estimate of their concentrations. In total, ten sample locations underwent this correction for quarry topography in the Hill of Fare granite.

Results

Heat production values of granite plutons

New gamma-ray spectrometry data were collected from 18 granite plutons (Table 1 and Fig. 3). The granites show a range of heat production values, with Strathspey the lowest at 1.20 $\mu W/m^3$ and Ballater the highest at 8.22 $\mu W/m^3$. Generally, with heat production any granite greater than 4 $\mu W/m^3$ is of interest for direct-use geothermal exploration as this value tends to be high enough to significantly raise the geothermal gradient over that of the surrounding rock (Gillespie et al. 2013). Additionally, 4 $\mu W/m^3$ corresponds to approximately a value of 10 in the old imperial units for heat production (i.e. 10^{-13} calories/cm^3). Naturally this is a guide and dependent upon local conditions; for instance, the unexposed Weardale granite in County Durham, England, has a heat production of 4.11 $\mu W/m^3$ but its insulating Carboniferous sedimentary overburden allows much higher temperatures to build up than the granite was exposed at the surface (Manning et al. 2007).

For this paper we adopt the convention that any granite pluton with a mean surface heat production above 5 $\mu W/m^3$ is considered high heat production, between 3 and 5 $\mu W/m^3$ is considered marginally high heat production (referred to as marginal heat production), and below 3$\mu W/m^3$ is low heat production. Four of the surveyed granites have high values of heat production; Ballater, Bennachie, Cairngorm, and Mount Battock (shown on Fig. 1). Five of the granites have marginal values of heat production; Ben Rhinnes, Cheviot, Hill of Fare, Lochnagar, and Monadhliath (shown in yellow on Fig. 1). Eight of the surveyed granites have low heat production; Aberdeen, Ardclach, Arran, Criffel, Strathspey, Grantown, Moy, and Ross of Mull (shown as grey on Fig. 1). The past heat production estimates were classified as "satisfactory" if there was sufficient quantity and spatial distribution of data (Downing and Gray 1986), however it was not stated what this meant. However, it is possible to infer that those plutons previously labelled as having satisfactory heat production estimates had more than ten samples from several locations in a pluton; for consistency this classification will be used in the following discussion.

The Lochnagar granite can be classified as marginal heat production, with a value of 3.89 $\mu W/m^3$. The lower historical value (2.7 $\mu W/m^3$) was classified as low confidence, possibly due to only having 14 heat production samples from the Lochnagar pluton. Downing and Gray (1984) classify granites with similarly few data as robust estimates, but do not specify why Lochnagar is not considered a robust estimate.

The Hill of Fare pluton previously only had two data points, far too few for the estimate of 3.9 µW/m^3 to be considered representative of the pluton. The new estimate, consisting of 31 data points, give a surface heat production average for of µW/m^3. The Hill of Fare therefore classified as a marginal heat producer.

The heat production estimate for the Monadhliath pluton is 4.98 µW/m^3. Although this is a marginal classification, it is only 0.02 µW/m^3 below a high heat production classification, it could therefore be reasonably classified as a marginal/high heat production granite. Only six measurement informed the previous heat production estimate for the Monadhliath pluton, but with the addition of the 17 new measurements then the current estimate would typically be considered representative of the pluton (i.e. following the method of Downing and Gray 1984). Lochnagar, Hill of Fare and Monadhliath are located relatively close to each other (Fig. 1) and are part of the same geochemical suite as the four high heat producing granites (Busby et al. 2015).

Cheviot and Ben Rhinnes were both previously estimated as low heat producers but these did not have enough data for confidence in these estimations (Fig. 4 and Table 1). The new heat production data indicate the Cheviot granite is marginal at 3.70 µW/m^3 which is higher than the previous estimate of 3.00 µW/m^3. There are still few data available for the Ben Rhinnes pluton, due to lack of exposure, but a combined mean of 3.33µW/m^3 suggests this granite is likely to be at the lower end of the marginal category.

Of the eight plutons classified as low heat production only Arran and Criffel previously had significant number of measurements, at 20 and 93 respectively. The plutons Moy, Ross of Mull, and Grantown had over ten measurements when the new and old data were combined. Even with the combination of new and old data Aberdeen (six measurements), Ardclach (seven measurements), and Strathspey (five measurements) are still currently poorly surveyed. The lack of exposure of these granites inhibits further field campaigns adding to these totals. However no measurements of these plutons were much greater than the mean, as shown by the small error bars on figure 3, which does not suggest that further measurements would be likely to reclassify these plutons.

Zoned plutons

Some granite plutons are concentrically zoned, with the zones differentiated on the basis of geochemical/mineralogical changes in composition (e.g. Stephens et al. 1985). Here we investigate whether these individual zones represent distinctive areas of high heat production within a pluton. Sufficient data were collected from two zoned plutons which would allow robust comparison between the individual zones. These are the Criffel Pluton in near Dumfries in South West Scotland, and the Cheviot Pluton which lies on the eastern area of the Scottish-English border (see Fig. 1 for specific locations).

Criffel Pluton

Work by Stephens et al. (1985), Stephens (1992) and continued by Miles et al. (2013) identified five zones of granite forming concentric rings within the Criffel Pluton (Fig. 5). The outer two zones (1 and 2) are granodiorites while the inner three zones (3, 4 and 5) are granites. The general trend is for the granite to become more silicic towards the inner zones, with the outer zone having SiO_2 at approximately 65% compared with 72% of the inner most zone (Stephens and Halliday 1980).

The highest value of heat production is in zone 2 (the most outer zone but one) with 2.51 µW/m^3, and the lowest is in the central zone 5 with 1.83 µW/m^3 (Fig. 6 and Table 2). From zone 2 to zone 5 there is a general trend for heat production to decrease towards the centre of the pluton. However the outermost zone 1 does not follow this trend. Although there are clear differences in the heat production, none of the zones are above 3 µW/m^3. All zones are considered as low heat production and unlikely to host enhanced geothermal gradients due to the natural decay of radioactive material.

Cheviot Pluton

The first detailed geological mapping of the Cheviot pluton was conducted by Jhingran (1942), who identified three main types of granite, an outer Marginal zone (1), an middle Granophyric zone (2), and an inner Standrop zone (3); with a fourth zone being an area that displays properties of the outer zones 2 and 1 (Fig. 7). The Cheviot pluton is surrounded by contemporaneous lavas. Al-Hadf (1985) subsequently produced a more detailed map of the Cheviot pluton; however this has not been peer-reviewed and published. Additionally we do not have enough data for the Cheviot pluton to provide robust differentiation between many granite types, for these reasons we use the Jhingran (1942) classification. The whole pluton is classified as granodiorite, except for some small areas of the middle Granophyric zone 2 which are true granite.

The outer marginal Zone 1 has the highest heat production of 4.16 µW/m^3, which would be enough to classify it as a marginal heat producing granite (Fig. 8 and Table 3). Zone 3 has a lower heat production of 3.51µW/m3, zone 2 also appears relatively low however only having one measurement means that this value cannot be considered representative of the zone. The surrounding lavas heat production, of 3.43 µW/m^3 is lower than that of the granites, however this value is surprisingly high for andesites. A possible explanation for the high heat production is the hydrothermal alteration of feldspar to saussurite (Lee 1982, Al-Hafdh 1985). Hydrothermal Alteration breaks down the structure of the minerals allowing remobilisation of the radioelements, which can result in high concentrations of radio-elements away from their emplacement location.

Discussion

Are there any reclassifications of geothermal potential for any Scottish granites?

Figure 4 compares our new heat production estimates with previous estimates for those plutons (cf Downing and Gray 1986 - their Table 3.9). Any significant divergence from the equivalence line would indicate a pluton that may require re-evaluation. Table 1 shows the mean surface estimate values plotted on figure 4 and then number of data used for each mean, in addition to the mean surface heat production of the combined new and historical data.

The four East Grampian granite plutons of Ballater, Bennachie, Cairngorm, and Mount Battock all have heat production rates in excess of 5 µW/m^3 , and are robustly characterised as high heat producers by both the new and historical data (Fig. 4 and Table 1). All four of these plutons are classified as part of the Cairngorm suite of post-Caledonian granites (Highton 1999).The new and historical data agree that Cairngorm, Mount Battock, Ballater, and Bennachie plutons are all high heat producers. However, the new estimates are generally higher than the historical estimates but not to the degree to require a significant re-appraisal of their geothermal potential. The new data show that four granite plutons should be reconsidered potential resources as marginally high: Hill of Fare, Monadhliath, Lochnagar, and Cheviot. The Hill or Fare, Lochnagar, and Cheviot granites were previously overlooked due to lack of data, and the few data available appeared to indicate that they would be low heat producers. Monadhliath was previously considered a high heat producer, but the few heat production data and poor accessibility meant it has achieved less attention than the four other high heat production granites. All of these plutons, with the exception of the Cheviot, are part of the Cairngorm suite, the same as the high heat producing granites..

The Hill of Fare pluton had only two previous measurements of heat production which gave a mean value of 3.9 µW/m^3 (Table 1). The new data (n=29) give a more robust value of 4.03 µW/m^3 when combined with the two previous data, which classifies the grantie as a marginal heat producer.

The Monadhliath granite was previously thought likely to be a high heat producer and potential geothermal resource. However, only six heat production data were collected on the Monadhliath granite. The new 17 data points show the Monadhliath granite being a comparable resource to the four high heat producing granites with a heat production of 4.98 µW/m^3, which is barely under the threshold to be considered a high heat producer.

The Lochnagar and Cheviot granites have, hitherto, been disregarded as potential geothermal resources, as they apparently had low heat production values of 2.7 µW/m^3 and 3.0 µW/m^3 respectively (Table 1). However, when our new data are considered then the Lochnagar granite is classified as a marginal heat producer at 3.89 µW/m^3 and the Cheviot granite is only slightly lower at 3.70 µW/m^3.

What is the significance of classifications for geothermal exploration?

The new gamma-ray spectrometry results confirm the classification of the high heat production granites i.e. Bennachie, Ballater, Cairngorm, and Mount Battock. These four granites are the most likely to have useful temperatures for direct use heat exploitation at the shallowest depths of the Scottish granites. And would therefore, present the most promising resources if there were nearby heat demands. This study also identifies those granites with low heat production, which are not expected to have useful temperatures at depths for an economic geothermal scheme. These low heat production granites include Arran and Strathspey on which there were previously no heat production data. All, apart from Grantown, of the low heat production granites previously had few measurements leading to uncertainty in their classification (Table 1). An example of the poor heat resource of these granites comes from a borehole (NJ91SE3 at UK national grid reference 395090 810900) which was drilled into country rock 3km adjacent to the Aberdeen granite. The borehole recorded a temperature of 32^{o}C at 1494m (Groves et al. 2012). Although the borehole is not directly in the granite a higher geothermal gradient would be expected if the granite itself had significantly elevated temperatures. The geothermal gradient found in this borehole is very low at around 13.4°C per km. This would require such great depths to be drilled to reach useful temperatures, that even a direct use geothermal project would be unlikely to be economic. Removing the uncertainty that these granites have poor geothermal resource, means that exploration effort can be focussed on those granites with favourable resources potential.

More crucially, marginal heat production granites have been identified, these are the Lochnagar, Monadhliath, Hill of Fare, and Cheviot granite as well as the Ben Rhines pluton to a lesser extent. These plutons could be viable geothermal resources if a heat-demanding development be proposed within close proximity to these granites. The Hill of Fare Pluton is of particular interest because it lies close to the large heat demand of the growing Banchory District Heating Scheme. For this reason, a feasibility study investigated using the Hill of Fare granite as a geothermal resource for the Banchory District Heating Scheme (The Scottish Government 2016b). The study predicted temperatures at depth within the Hill of Fare Pluton (Table 4). These predicted geotherms are sufficient for direct use geothermal to compete economically with a natural gas boiler over the lifespan of a project; in addition to the significant emissions advantage over natural gas and air quality advantages over biomass. This suggests, that geothermal exploration in Scotland can rightly expand, beyond merely the four high heat production granites, to also consider the marginal heat production granites as targets.

Robust values of heat production are the first step in the geothermal exploration process of radiothermal granites. The simple ranking system, proposed in this paper, builds the framework upon which the next stage of the exploration process can be targeted towards the granites which are most likely to have favourable geothermal gradients, i.e. the high and marginal heat production granites. The next stage in the appraisal of these granites would require deep scientific boreholes of 1000m and greater depth. The kilometre depth of these scientific boreholes is required to provide certainty of the heat resource, due to past experience of the misleading heat flow that shallow boreholes can present (Westaway and Younger 2013 and Busby et al. 2015). The scientific borehole would provide information about heat and permeability at depth (cf Manning *et al.* 2007; Younger and Manning 2010), which would create the information required to justify commercial exploration boreholes.

Could the higher heat production outer rims of the zoned granites be a potential geothermal resource?

Significant variations in heat production can exist with a pluton made up of distinct geochemical zones. Here, we discuss the possibility of these distinct high heat production zones offering a potential geothermal exploration target within an otherwise discounted granite. We do not explore the emplacement and post-emplacement processes which have led to zonal differences in concentrations of potassium, uranium, or thorium but focus on the potential geothermal resource that these differences could pose. However there is much scientific and applied merit in investigating these processes further as they could elucidate how heat production may change with depth (particularly in relation to 3D geometry) and help reduce the risk of the geothermal exploration process within granite.

The investigation of the Criffel pluton shows that there were heat production differences between the geochemically distinct zones of the granite (Figures 7 and 8). However none of these zones were of high heat production, so these differences are not considered significant for geothermal exploration of this pluton.

In the Cheviot granite all the zones would also individually be classed as a marginal heat producer, except for the outermost zone 1 which has a heat production of about 4 $\mu W/m^3$. Zone 1 was significantly higher (by 0.47 $\mu W/m^3$) than the next highest heat production which was zone 2, however zone 2 only had one measurement so can not be considered a reliable estimate. This outer zone 1 may have high enough heat production to be regarded as a possible geothermal target but it has a relatively small surface area compared to the uniformly high heat producing granites. For comparison the surface area of the Bennachie pluton is 55 km^2 whereas the surface area of the marginal zone 1 of the Cheviot Pluton is 14 km^2. Zone 1 only represents 25% of the entire Cheviot Pluton surface area. There are some Scottish granites which are high heat producing and have small surface areas, e.g. the Fearn Pluton (5.1 $\mu W/m^3$, 12 km^2) located north of the Great Glen Fault (Fig. 3.3 in Downing and Gray 1986). These small surface area granites have not been considered for geothermal resources as their likely low volume at depth may not allow heat to sufficiently accumulate from the heat production. Although their surface area may be misleading and actually be part of a significant volume of granite at depth (i.e. similar to the tip of the iceberg). However the small surface area of high heat production couple with the uncertainty of the three dimensional shape of the granites mean that these zoned granites are unlikely to be favourable exploration targets. For these reasons, exploration has been focussed on those granites known to have significant subsurface volumes due to their large surface areas. The heat production data do not support a change to this approach. For the Cheviot Pluton a model of how the different granite types are distributed at depth would help constrain how much of the volume of the Cheviot Pluton is the higher heat producing zone. The Cheviot Pluton could still represent an interesting geothermal target if it is likely that zone 1 encompasses a larger proportion of the volume than its surface area suggests.

Conclusions

High heat production Scottish granites are identified as the Ballater, Bennachie, Cairngorm, and Mount Battock plutons. These four are likely to be the best granite-based geothermal resources in Scotland.

Marginal heat production granites are identified as the Ben Rhinnes, Cheviot, Hill of Fare, Lochnagar, and Monadhliath plutons. Although these granites may not present such a favourable geothermal resource as the high heat producers, they are still worth investigating as a supply to any proximal large heat demand.

Low heat production granites are identified as Aberdeen, Ardclach, Arran, Criffel, Strathspey, Grantown, Moy, and Ross of Mull. These granites are very unlikely to offer geothermal gradients of interest for economical direct use of heat. As such, they would be unlikely to be worth further exploration if a large heat demand existed in the vicinity of these granites.

Zoned granites are unlikely to present geothermal resources within specific geochemical zones. The relatively small surface area and likely small volume of any single higher heat production zone means that they are unlikely to create large reservoirs of elevated temperature at depth.

This study shows the value that a relatively quick and simple gamma-ray spectrometry survey can set initial targets for geothermal exploration into granite plutons. The classifications of high, marginal, and low heat production provide a basis for exploring the possibility of exploiting direct-use geothermal heat by any future development with large heat demands.

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Figure Captions

Fig. 1. Map showing locations of major exposed granite plutons in Scotland. Numbered plutons are those surveyed in this study. 1 Moy, 2 Ardclach, 3 Ben Rhinnes, 4 Grantown, 5 Monadhliath, 6 Bennachie, 7 Cairngorm, 8 Ballater, 9 Hill of Fare, 10 Aberdeen, 11Strathspey, 12 Lochnagar, 13 Mount Battock, 14 Ross of Mull, 15 Arran, 16 Cheviot, 17 Criffel. Plutons identified in this study as high heat producing are 6, 7, 8, and 13, those identified as marginally high heat producing are (3, 5, 9, 12, and 16).

Fig. 3. Schematic of simplified quarry topography. The GSII spectrometer is calibrated assuming a 2π sample volume, but the quarry topography led to an effective sample volume of approximately 3π.

Fig. 3. Mean surface heat production estimates for surveyed plutons in this study. Whiskers on the icons are the standard error of the mean (standard deviation divided by the square root of the number of data).

Fig. 4. Mean surface heat production estimates from figure 3 (y-axis) compared with historical estimates (x-axis) given in table 3.9 in Downing and Gray (1986). Dotted line shows equivalence line. Hollow circles show the estimates which Downing and Gray (1986) stated there was inadequate data to derive a satisfactory heat production estimate. Arran and Strathspey granites are not included in this graph as these plutons had no previous heat production data.

Fig. 5. Map of the different geochemical zones within the Criffel Pluton, after Miles et al. (2013). Dotted lines show areas where sample points are clustered.

Fig. 6. Mean surface heat production values for the zones of the Criffel Pluton .

Fig. 7. Map of the different geochemical zones within the Cheviot Pluton, after Jhingran (1942). Dotted lines show areas where sample points are clustered.

Fig. 8. Mean surface heat production values for the zones of the Cheviot Pluton. Note zone 2 only had one measurement so does not include standard error.

Table 1 *Number of data and surface heat production estimate for each pluton from the new data presented in this paper and the historical data from Downing and Gray (1986; their Table 3.9), and then the combined surface heat production estimate from new and historical data. *Indicates historical data with low confidence attached to the estimate.* **+** criteria for re-evaluation are classified as follows: (1) few existing heat production data, (2) located near places of significant heat demand, (3) previously considered a high heat producing granite

Table 2 *Mean surface heat production values for the zones of the Criffel Pluton.*

Table 3 *Mean surface heat production values for the zones of the Cheviot Pluton*

TABLE 4 *Predicted temperatures in the Hill of Fare granite for three "heat scenarios" from The Scottish Government (2016b).Temperatures were calculated assuming a related but lower heat flow to that measured in the nearby high heat producing granites.*